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Spatial Nonlinear Simulation Analysis on the Temperature Shrinkage Effect of a Super-Long Frame Structure Considering the Construction Process

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Abstract: The temperature shrinkage effect is a very important factor causing the cracking of super-long frame structures. Current design codes and recommendations for reinforced concrete (RC) structures consider the influence of the construction process on the temperature shrinkage effect by adopting a uniform reduction coefficient and neglect the influence of the construction method. However, different construction processes can vary the temperature stress of the structure. In this paper, under cooling action, the temperature stress of a one-layer, super-long frame structure with different quantities and indwelling times of post-cast strips is calculated with a spatial nonlinear simulation analysis program by adopting the degenerated spatial solid virtual laminated element method. With this approach, the internal force state of each construction stage during the construction process is accounted for in a nonlinear mechanical model of the structure. The results show that the quantity and the indwelling time of post-cast strips can effectively vary the temperature stress of the structure. Meanwhile, the quantity of the post-cast strips can have a more obvious effect than the indwelling time. Therefore, the construction process is an important factor affecting the temperature shrinkage effect of the structures. The research results can provide a valid reference for the design and construction of super-long frame structures.

Keywords: super-long frame structure; temperature shrinkage effect; construction process

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1. Introduction

Under restraint conditions, the volume deformation (autogenous shrinkage, drying shrinkage and thermal deformation) of concrete will induce stress (mostly tensile stress) in early age concrete [1]. An expansion joint is a structural component designed to provide smooth passage over a gap between adjacent sides of a structure and is an effective measure of declining temperature stress. The Chinese design code of concrete structures [2] defines a super-long frame structure as one in which the spacing of the expansion joint is more than 55 m. However, many super-long frame structures have been designed without the expansion joint to maintain the aesthetics of the building and the integrity of the structure [3–6]. Ha [3] finished the super-long structural design of a shopping center by comprehensively applying traditional anti-cracking technology and new technology of releasing temperature stress. Ma [4] solved the over-length problem of a cultural and art center by temperature stress analysis and the constructive method. Ge [5] effectively reduced the impact of temperature stress on a super-long medical building structure by reasonably using materials combined with the corresponding structural measures. Shi [6] found that reasonable construction measures can reduce the influence of temperature load during the structural design of a large commercial building. Thus, setting post-cast strips at the construction stages is one of the important means of solving the over-length problem. Since the tensile strength of concrete is significantly lower than the compressive strength, cooling action has more negative effects on the concrete structure than heating action [7].

Therefore, research on the temperature shrinkage effects of super-long frame structures considering the construction process is of great significance.

In view of the temperature shrinkage effects of super-long frame structures, many scholars have carried out the related research [8–18]. Due to the large dispersion and complexity of structural performance testing in experimental research and demonstration engineering applications, simulation techniques are important solutions to the temperature shrinkage effect problems of super-long frame structures. Wang [19] launched targeted research on a super-long frame structure without an expansion joint and concluded that the construction process can vary the temperature stress distribution. Quan [20] concluded that the quantity of continuous reinforcement, the width of the post-cast strip and the position of the gravity center of the continuous reinforcement have a significant effect on the constraint force. Zhang [21] analyzed the key factors that affect the function of post-cast strips in super-long frame structures and the interrelationships among the key factors. Li [22] carried out a nonlinear analysis of temperature stress and temperature effects on overly long concrete using the large finite element software ANSYS and provided a reference for structural measures and construction measures of reinforced concrete structures. Jia [23] analyzed the influence of the difference in the linear expansion coefficients of steel and concrete on the temperature stress of super-long frame structures. Thus far, the construction process has usually been considered by using a uniform reduction coefficient in the analysis of the structures, neglecting the internal force redistribution of the structure during the construction process. It is necessary to consider the influence of the construction process and the difference in the linear expansion coefficients of steel and concrete on the temperature shrinkage effect of super-long frame structures.

In order to analyze the internal force redistribution of a structure during the construction process and to understand the influence of the construction process on the temperature shrinkage effects of super-long frame structures, a more accurate and efficient analysis method should be proposed to fill the relevant research gaps in this field. For meeting such analytical requirements, this paper presents a spatial nonlinear simulation analysis program by adopting the degenerated spatial solid virtual laminated element method. This program can effectively calculate and accumulate the internal force state of a structure after each construction stage for comparing and analyzing the influence of the construction process on the temperature shrinkage effects of super-long frame structures.

2. Simulation Method of Temperature Shrinkage Effect

The degenerated spatial solid virtual laminated element [24] was put forward by combining the theory of the degenerated solid element [25] and the theory of the virtual laminated element [26] on the basis of the traditional spatial isoparametric solid element. It can conveniently consider the mechanical properties of the various components of a structure, such as a column, beam and plate, etc., by modifying the matrix of the elastic coefficient or restricting the relative displacement of the element's nodes. The degenerated spatial solid virtual laminated element generally has the same degrees of freedom as the traditional spatial isoparametric solid element. Due to there being no rotational degree of freedom, it can conveniently connect with other elements for an analysis of a whole super-long frame structure. The basic assumption of the global coordinate system of x, y, z about the degenerated spatial solid virtual laminated element can be seen in the literature [25]. The displacement function of the degenerated spatial solid virtual laminated element is the same as that of the traditional spatial isoparametric solid element. When the constitutive equations and displacement function are known, the element stiffness matrix and whole stiffness matrix can be deduced. The specific process of deduction can be seen in the literature [27].

In order to increase the efficiency of spatial analysis and model construction, the technique of integrating subsections is introduced in the calculation of the stiffness matrix of the degenerated spatial solid virtual laminated element. In other words, one element can be divided into several segments or layers, in which the empty zone is taken as one virtual segment or layer. The element stiffness matrix is the sum of the integral value of each segment or layer, and the integration of the stiffness matrix in the virtual segment or layer is zero. Thus, the stiffness matrix of element $[K_{ij}]$ can be written as follows:

$$[K_{ij}] = \sum_{k=1}^{nm} \int_{-1}^{1} \int_{-1}^{1} \int_{-1}^{1} \left[B_i\left(\xi^k, \eta^k, \zeta^k\right)\right]^T [D^k] \left[B_j\left(\xi^k, \eta^k, \zeta^k\right)\right] |J||J'| d\xi' d\eta' d\zeta' \quad (1)$$

where $\xi' \in [-1, 1]$; $\eta' \in [-1, 1]$; $\zeta' \in [-1,1]$; n is the number of inner nodes of the kth segment or layer, and the value of n is 20; ξ^k, η^k and ζ^k are the mother coordinates of any point in the kth segment or layer; m is the number of segments or layers in the element; B_i, B_j comprise the strain matrix of the traditional spatial isoparametric solid element; D^k is the elastic matrix of the kth segment or layer; and $|J|$, $|J'|$ are the Jacobian coordinate conversion of the element and segment, respectively.

Therefore, the element can be divided into different segments or layers based on the features of column, beam and plate, whose material characteristics of concrete and steel can be assigned different temperatures and linear expansion coefficients, as shown in Figure 1.

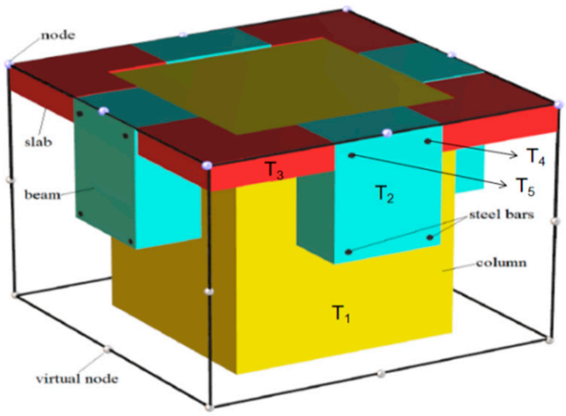


Figure 1. Block division of the element.

In addition, the degenerated spatial solid virtual laminated element can take into account the double geometric and material nonlinearity. In terms of geometric nonlinearity, the method adopts the complete Lagrange format [28] (T.L. method) to analyze the temperature effects of super-long frame structures. As for the material nonlinearity, the multiple strengthening plastic model assumed by Ohtani and Chen [29] is adopted for the concrete, whereas the ideal elastic-plastic model is employed for the steel. To consider the multi-direction cracking at an integral point, an orthogonal distribution crack model is used to simulate the concrete crack. The failure condition of the three-parameter strengthened plastic model defined by Ohtani and Chen [29] is applied to define the failure criterion of concrete. Failure is defined when the concrete strain reaches the ultimate strain, where three-dimensional cracking of the concrete is included. Furthermore, the shape and displacement of the reinforcement are described by a three-node, one-dimensional isoparametric element. Nonlinear equations are solved by the mN-R iterative incremental method [28].

In order to consider the construction process of a super-long frame structure, it is necessary to analyze the internal force change or the conversion of the internal force system in each construction stage during the construction process. According to the division of the construction process of super-long frame structures, the internal force state is calculated at the end of the first construction stage, whose internal force, displacement, cumulative shaping strain and material damage are fed into the next construction stage. Finally, the internal force state of the structure, including internal force, displacement, cumulative shaping strain and material damage, is obtained when the construction is completed.

As stated above, a spatial nonlinear simulation analysis program was developed based on the method, which can consider the material and geometric nonlinearity during the construction process and performs the stage calculation analysis of structures according to the construction process. The advantages and applicability of the degenerated spatial solid virtual laminated element method as an effective solution to the temperature shrinkage effect problems of these structures have been verified in the literature [23]. Therefore, the program is applicable for analyzing the temperature shrinkage effect of super-long frame structures considering the construction process.

3. Research on Temperature Shrinkage Effect of Super-Long Frame Structure

3.1. Modeling Design

To analyze the temperature shrinkage effect of super-long frame structures considering the construction process, a one-layer reinforcement concrete super-long frame structure with a length of 17 × 7 m, a width of 3 × 6 m and a height of 3 m was designed in accordance with the Chinese design code of concrete structures [2]. The geometric size of the sections and the reinforcing details are shown in Figure 2. The material properties are given in Table 1.

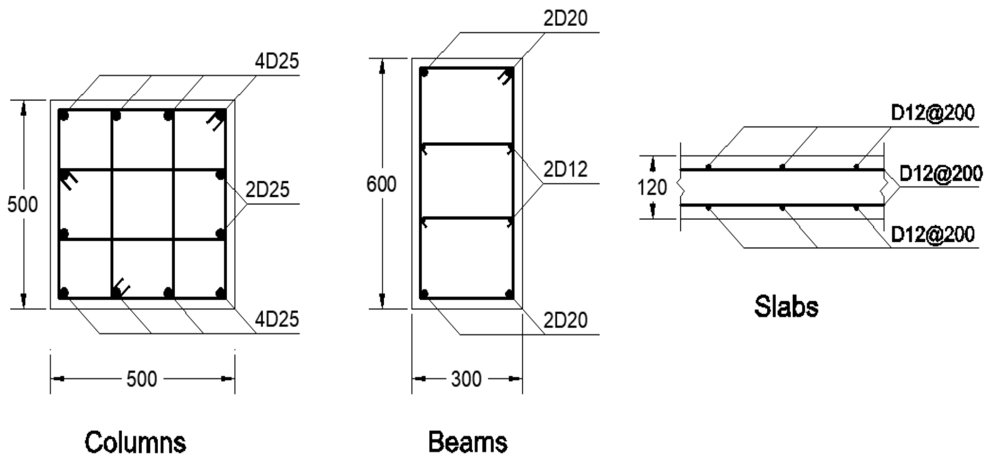


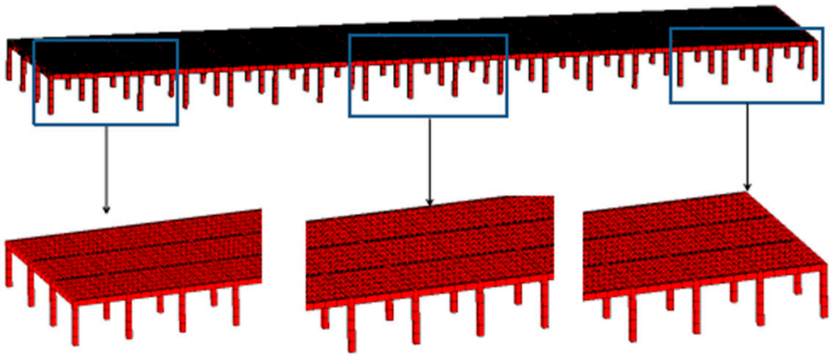
Figure 2. The geometric cross-section size and reinforcement details (unit: mm).

Table 1. Material properties.

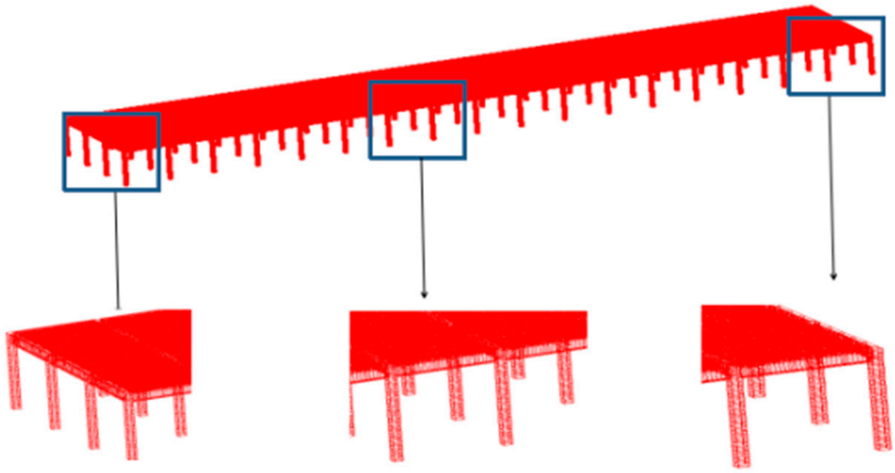
Concrete (C30)	
Density (ρc)	2600 kg·m^{-3}
Poisson's ratio (νc)	0.2
Young's modulus (Ec)	30 GPa
Aver. comp. strength (fck)	20.1 MPa
Aver. tensile strength (fctk)	2.01 MPa
Linear expansion coefficient (αc)	0.00001 °C^{-1}
Steel (HRB400)	
Density (ρs)	7800 kg·m^{-3}
Poisson's ratio (νs)	0.3
Young's modulus (Es)	200 GPa
Aver. yield strength (fsyk)	400 MPa
Linear expansion coefficient (αs)	0.000012 °C^{-1}

3.2. Modeling Analysis

The analysis model of the one-layer super-long frame structure was established by the spatial nonlinear simulation analysis program by adopting the degenerated spatial solid virtual laminated element method, which can consider the material properties of concrete and reinforcement, temperature action and the construction process, as shown in Figure 3.



(a)



(b)

Figure 3. Vertical view of the finite element model: (**a**) Mesh model; (**b**) Reinforcing bars model.

Setting post-cast strips during the construction process is one of the important means of mitigating the adverse effects caused by temperature action. To simulate the construction process, differences in the construction process were reflected by the quantity and the indwelling time of post-cast strips, and the temperature loads were applied in stages according to the setting of the post-cast strips. Since the tensile strength of the concrete is significantly lower than the compressive strength, the temperature stresses caused by the cooling action are the main indicators in the analysis of the effect of the structure. To analyze the plastic development process of the concrete cracking, the following incremental schemes were adopted: the model was uniformly cooled as a whole and loaded from -1 to -30 °C, while the structure was only subjected to the cooling effect without the self-weight load.

In order to analyze the action of the post-cast strip on the temperature stress of the structure, the variation in and distribution of temperature stress caused by the quantity and the indwelling time of the post-cast strips were simulated and calculated, and the results were used to analyze the influence of the construction process on the temperature stress of the super-long frame structure. Thus, six working conditions have been used in this paper to assess the performance of the structure, numbered from one to six; the details are shown in Table 2, and the detailed locations of the post-cast strips are shown in Figure 4.

Table 2. Working condition details.

Condition Number	Post-Cast Strip Quantity	Location	Indwelling Time (d)	Temperature Difference (−°C)
1	None	/	/	−30
2	One	9th span	45	−30
3	Two	6th and 12th span	45	−30
4	One	9th span	15	−30
5	One	9th span	30	−30
6	One	9th span	60	−30

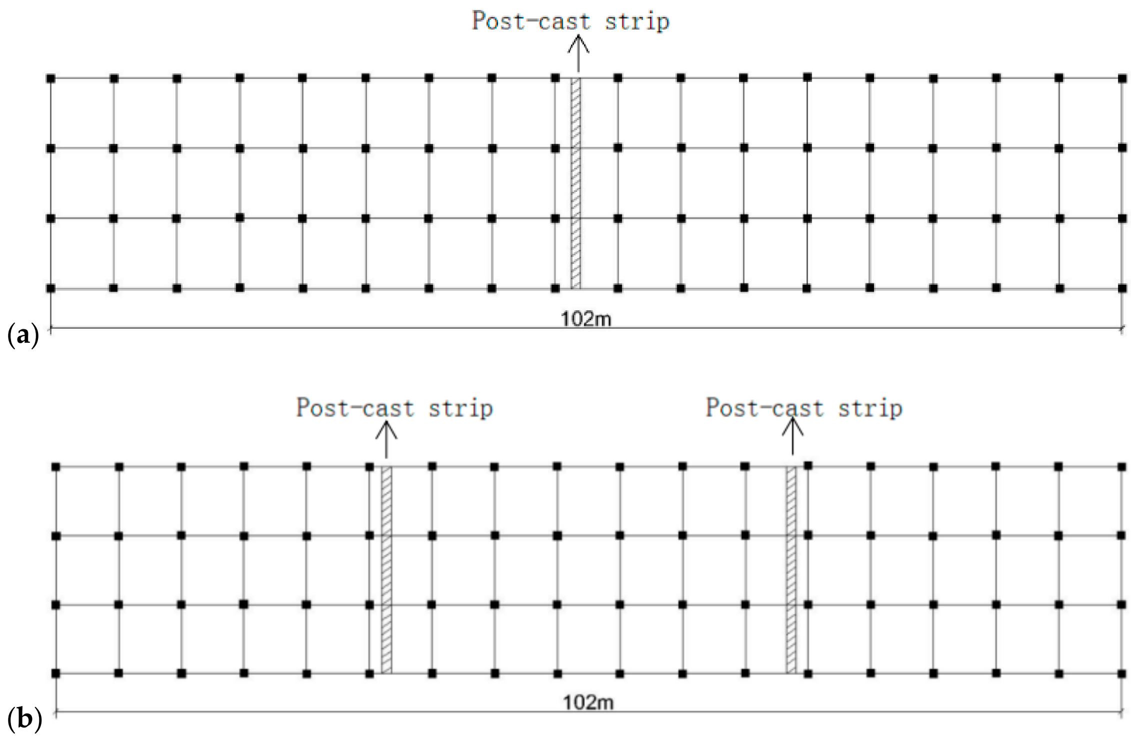


Figure 4. Location of post-cast strips: (**a**) One post-cast strip; (**b**) Two post-cast strips.

3.3. The Calculated Temperature Difference

The models of the structure considering the construction process were divided into two phases: modeling before and after casting the post-cast strip, as shown in Figure 5.

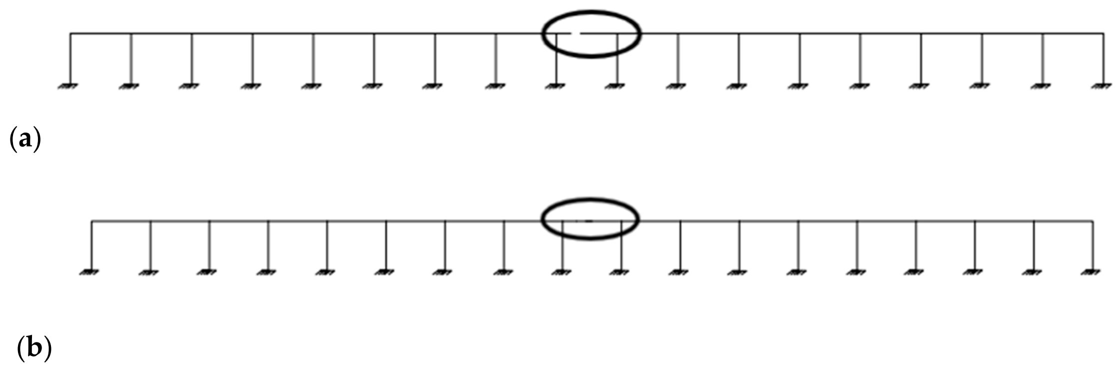


Figure 5. Modeling before and after casting the post-cast strip: (**a**) Before casting the post-cast strip; (**b**) After casting the post-cast strip.

The calculated temperature difference before casting the post-cast strip was obtained by summing the seasonal temperature difference and the equivalent temperature difference of concrete shrinkage, whereas the calculated temperature difference after casting the post-cast strip is the sum of the creep relaxation coefficient multiplied by the seasonal temperature difference and the equivalent temperature difference of concrete shrinkage. According to the literature [30], the creep relaxation coefficient is 0.6.

Before casting the post-cast strip, the seasonal temperature difference obtained by subtracting the maximum temperature in the construction stage from the casting temperature was −1.6 °C. After casting the post-cast strip, the seasonal temperature difference obtained by subtracting the casting temperature from the lowest temperature during the service life of the structure was −30 °C.

According to working condition 1 and working condition 2, 50% of the total shrinkage was completed before casting the post-cast strip. According to the literature [19], the total shrinkage of concrete is calculated as follows:

$$\boldsymbol{\varepsilon_y(t)} = \boldsymbol{\varepsilon_y^0} \cdot \boldsymbol{M_1} \cdot \boldsymbol{M_2} \cdot \boldsymbol{M_3} \cdots \boldsymbol{M_n}\left(1 - \mathrm{e}^{-\boldsymbol{bt}}\right) \tag{2}$$

Meanwhile, the equivalent temperature difference of concrete shrinkage is calculated as follows:

$$T_y = \frac{\varepsilon(t)}{\alpha} \tag{3}$$

The meaning of each symbol in the above formula is described in the literature [19].

Through the above analysis process, the calculated temperature difference before casting the post-cast strip was −22.7 °C, whereas the calculated temperature difference after casting the post-cast strip was −30.7 °C.

4. Results and Discussion

Under the cooling action of the structure, the slabs were greatly affected by the temperature difference due to the restraint of beams and columns; meanwhile, the post-cast strips were set on the slabs. The results of the temperature stress analysis of the slabs are shown in this chapter, including the six different working conditions, according to the quantity and the indwelling time of the post-cast strips in the super-long frame structure.

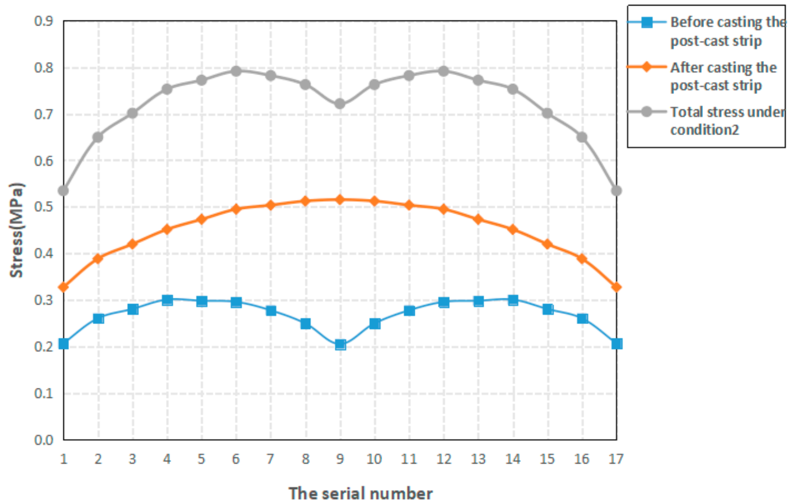
4.1. Impact Analysis of the Quantity of Post-Cast Strips

This part mainly compares and analyzes the temperature stress of the slabs of the structure under three different working conditions (working conditions 1 to 3), and the results are used to evaluate the influence of the quantity of post-cast strips on the temperature stress of the slabs.

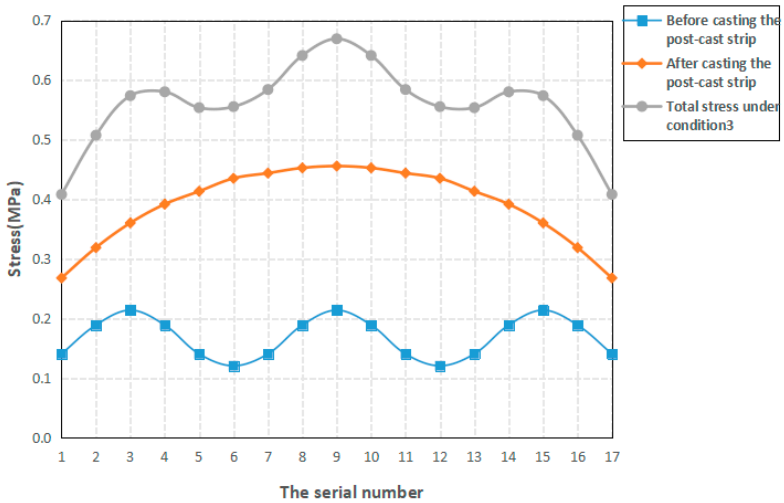
Figure 6 shows the distribution of the temperature stress of the slabs located in different positions of the structure under the three working conditions (working conditions 1 to 3). The data on the *X*-axis represent the serial number of the slabs located in different parts of the structure, and the data on the *Y*-axis represent the temperature stress of the slabs.

It can be observed from the figure that the quantity of post-cast strips can affect the distribution of the temperature stress of the slabs, and the distribution varies with the location of the slabs in the structure.

Figure 6a shows the stress variation before and after casting the post-cast strip, in which the stress at the post-cast strip zone is obviously reduced. Thus, the post-cast strip is beneficial for reducing temperature stress. The same conclusion can be obtained from Figure 6b. In addition, increasing the quantity of post-cast strips can make the temperature stress of the slabs more evenly distributed. According to Figure 6c, the stress difference in the slabs under the three working conditions (working conditions 1 to 3) is very obvious; the largest stress happening under working condition 3 is 0.77 times that under working condition 2 and 0.46 times that under working condition 1. Thus, the post-cast strip can obviously reduce the temperature stress of the slabs. However, with the increase in the quantity of post-cast strips, the efficiency in reducing the temperature stress will decrease gradually.



(**a**)



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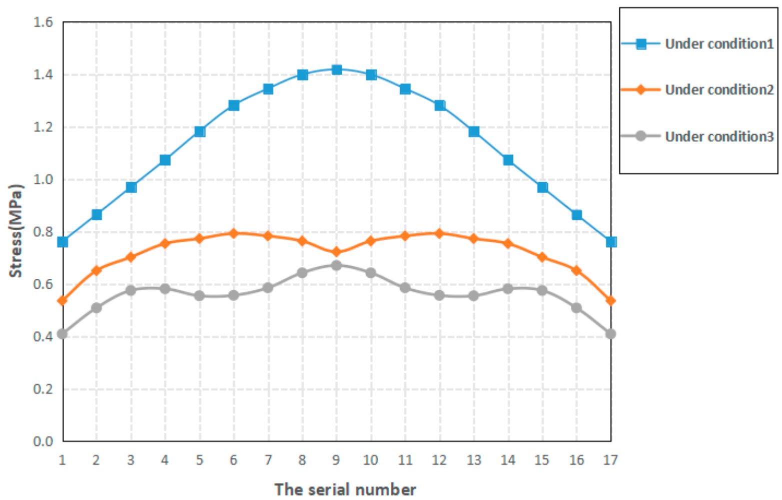

(**c**)

Figure 6. Stress profiles under three working conditions: (**a**) Condition 2; (**b**) Condition 3; (**c**) Conditions 1, 2 and 3.

Therefore, the quantity of post-cast strips should be determined according to the temperature stress analysis and the specific construction conditions.

4.2. Impact Analysis Based on the Indwelling Time of Post-Cast Strips

This section mainly compares and analyzes the temperature stress of the slabs of the structure under four different working conditions (working condition 2 and working conditions 4 to 6), and the results are used to evaluate the influence of the indwelling time of the post-cast strips on the temperature stress of the slabs.

Figure 7 shows the distribution of the temperature stress of the slabs located in different positions of the structure under the four different working conditions (working condition 2 and working conditions 4 to 6), which can be used to compare the influence of indwelling time when setting one post-cast strip according to Table 2. The data on the X-axis represent the serial number of the slabs located in different parts of the structure, and the data on the Y-axis represent the temperature stress of the slabs.

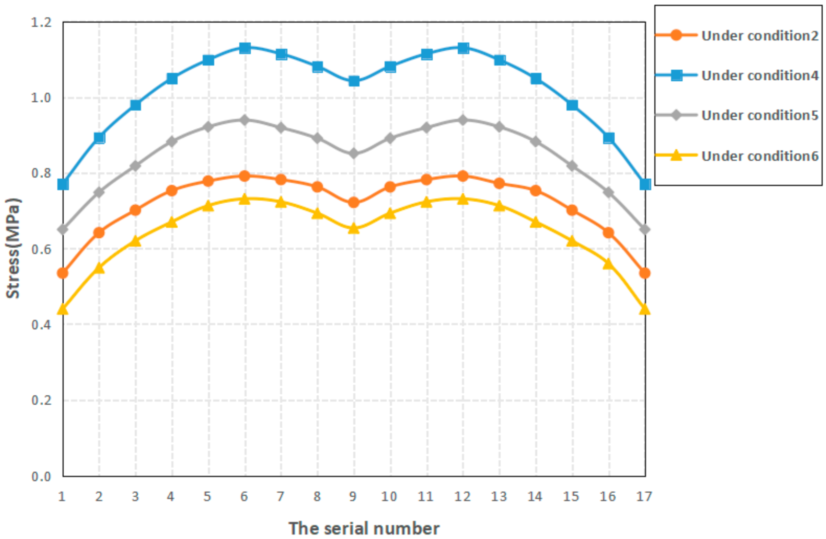

Figure 7. Stress profiles under four working conditions (working condition 2 and working conditions 4 to 6).

It can be observed from the figure that the indwelling time of the post-cast strip can affect the distribution of the temperature stress of the slabs, and the distribution varies with the location of the slabs in the structure.

Figure 7 shows the stress variation with the different indwelling times of the post-cast strip, in which the distribution of the temperature stress under different working conditions is similar. When the indwelling time of the post-cast strips is 15, 30, 45 and 60 days, the maximum temperature stress of the slabs is 1.05, 0.75, 0.66 and 0.58 MPa, respectively. With the increase in the indwelling time of the post-cast strip, the temperature stress decreases gradually; however, the efficiency in reducing the temperature stress also decreases gradually.

Therefore, the indwelling time of the post-cast strip should be determined according to the temperature stress analysis and the specific construction conditions.

Based on a comprehensive look at the above two analysis results, setting post-cast strips at the construction stages is an important means of redistributing the internal force of the structure during the construction process, and the quantity of the post-cast strips can have a more obvious effect than the indwelling time.

5. Conclusions

A one-layer reinforcement concrete super-long frame structure model has been built with the spatial nonlinear simulation analysis program by adopting the degenerated spatial solid virtual laminated element method. In the model, the construction process was explicitly simulated with different quantities and indwelling times of post-cast strips and analyzed by calculating the internal force state of each construction phase. In order to clearly research the influence of the construction process on the temperature shrinkage effect of a super-long frame structure, the results of the temperature stress analysis of the slabs were addressed in this paper. Based on the research presented in this paper, the following conclusions can be drawn:

(1) In the temperature shrinkage effect analysis of the super-long frame structure considering the construction process, it was found that the quantity and the indwelling time of the post-cast strips can vary the temperature stress distribution with the position of slabs in the structure.
(2) Post-cast strips can obviously reduce the temperature stress of slabs. However, with the increase in the quantity of post-cast strips, the efficiency in reducing the temperature stress decreases gradually.
(3) The indwelling time of post-cast strips can also affect the temperature stress of slabs. With the increase in the indwelling time of post-cast strips, the temperature stress decreases gradually; however, the efficiency in reducing the temperature stress also decreases gradually.
(4) Post-cast strips can change the strain on super-long frame structures during the construction process and vary the temperature stress of the slabs in the structure under different working conditions; their quantity and indwelling time should be determined according to the temperature stress analysis and the specific construction conditions. Therefore, the design of post-cast strips can effectively vary the temperature shrinkage effect of a super-long frame structure and should be seriously considered during the construction process.
(5) This paper presents an accurate and efficient method to analyze the influence of the construction process on the temperature shrinkage effect of super-long structures and provides a valid reference for the design and construction of super-long frame structures. However, more construction parameters and tests need to be studied in the future.

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